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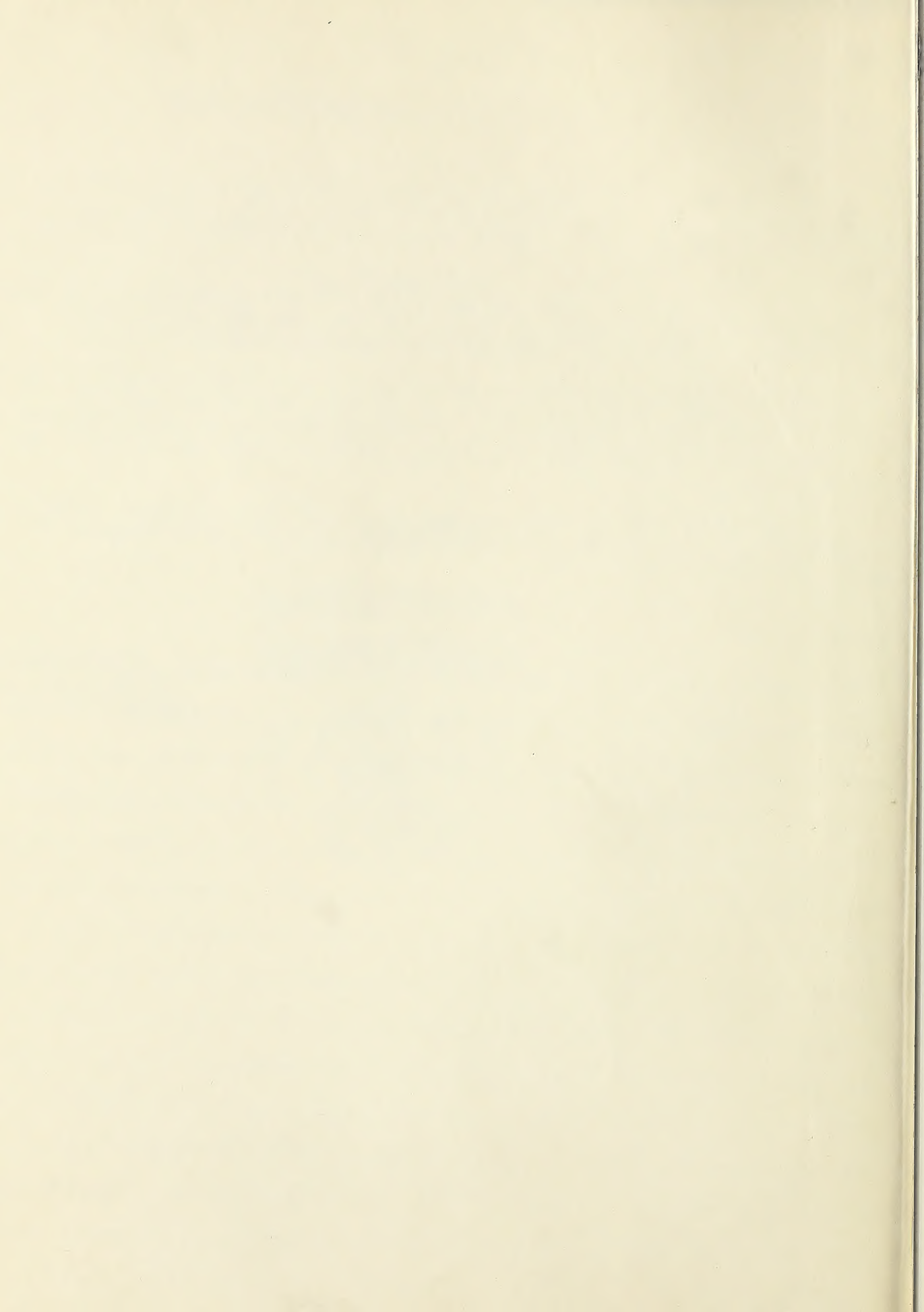
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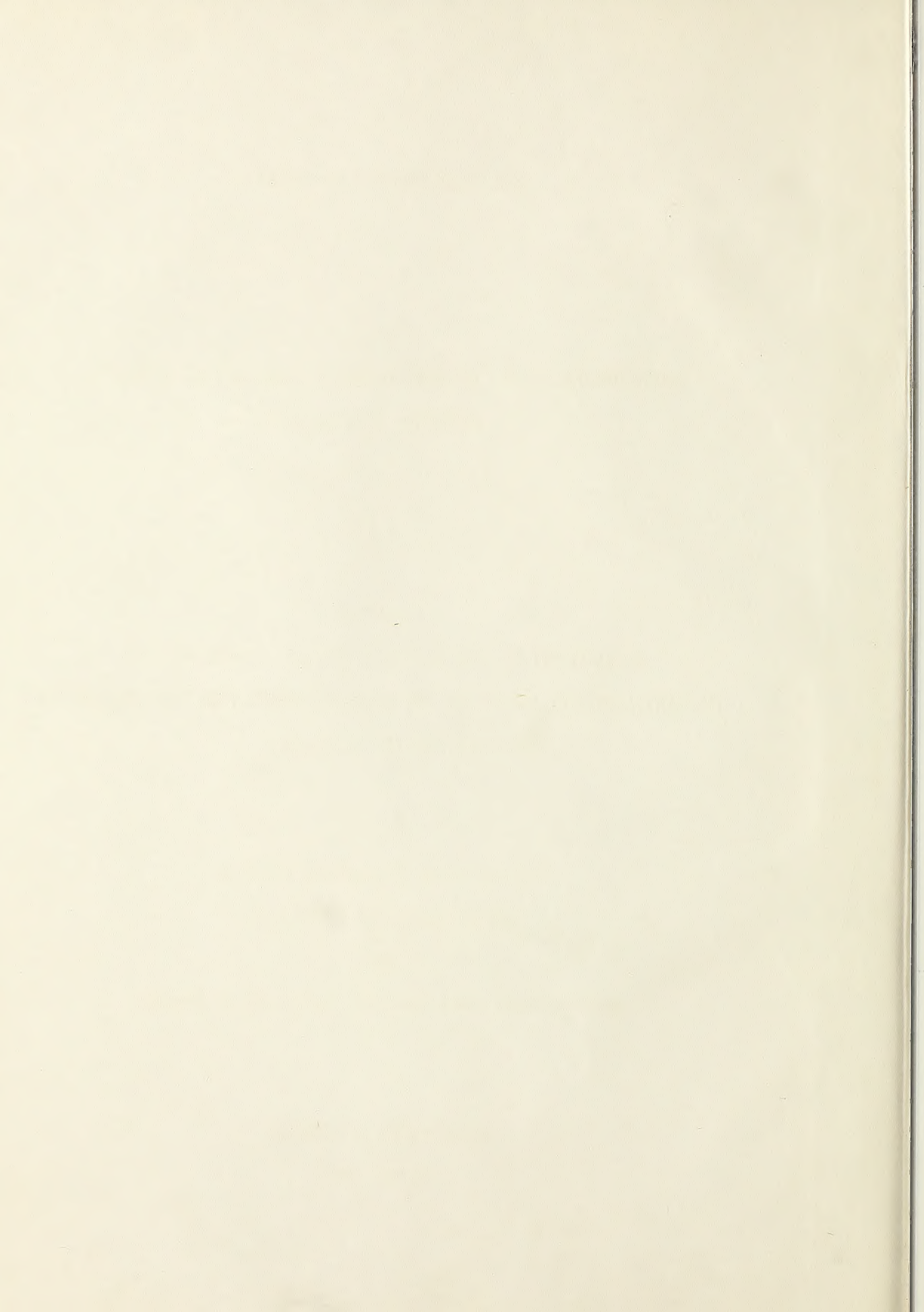




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GEOCHRONOLOGY OF CRETACEOUS-TERTIARY BOUNDARY,
ALBERTA, CANADA

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF
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ABSTRACT

The exact stratigraphic position of the Cretaceous-Tertiary boundary in Alberta is controversial because of limited continental faunal and floral evidence. Twenty six K-Ar dates obtained from Alberta bentonites, together with eleven previously obtained, place the time boundary at 63 ± 1 million years. There is no significant break in the depositional record at the Cretaceous-Paleocene boundary in central Alberta. Sanidine from bentonites gives more reliable dates than co-genetic biotite. Biotite when leached gives a date which is too young. K_2O/Rb_2O ratios in biotite suggest three stratigraphic groups of bentonite beds which may represent three periods of volcanic activity during continuous uppermost Cretaceous-Paleocene continental deposition. [The Kneehills Tuff (66 m.y.), bentonites in diachronous coal beds of the Cretaceous-Tertiary boundary (63-60 m.y.), and younger Paleocene bentonites (approximately 55 m.y.)]. No significant variation either in chemical composition or mineral constituents is apparent between 10 Cretaceous and 8 Paleocene analysed bentonites from near the Cretaceous-Tertiary boundary.

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Mr. Frank Dimitrov drafted the plates, and Miss S. Baker typed the manuscript.

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INTRODUCTION

CRETACEOUS-TERTIARY BOUNDARY PROBLEM

The Cretaceous, the last Period of the Mesozoic Era, was the age of dinosaurs. Towards the end of the Cretaceous, changes in topography, climate and environmental conditions took place all over the world and resulted in profound changes in existing faunas. The strain of changing conditions seems to have become so severe that large and important animal groups on land, in the sea and in the air, such as dinosaurs, ammonites, belemnites and flying reptiles were exterminated. The exact cause of these worldwide extinctions is not yet known. Mammals replaced the Mesozoic land fauna and became dominant with the dawn of the Cenozoic Era. The boundary between the Cretaceous and Tertiary Periods is defined by this world wide faunal break between the age of reptiles and the age of mammals.

The resolution of the Cretaceous-Tertiary boundary problem hinges on two subordinate aspect of paleobiology:

- a) The Cretaceous-Tertiary boundary may be delineated on the basis of invertebrate fauna in marine environments, but for the continental deposits, extinction of dinosaurs is critical. Correlation between the two is a matter of extensive synthesis of detail not yet completed.
- b) There are breaks in the fossil record due to the "great dying out" at the end of the Cretaceous Period. In most places, highest fossil bearing Cretaceous strata are separated from lowest known Paleocene fauna by an uncertain interval without any diagnostic fossils. Absence of fossils may be due to local lack of preservation, diastemic or erosional breaks, or actually represent the extinction of life forms that were being used to zone the earlier strata. This is a matter of local resolution and data locally obtained can not always be used for regional correlations.

The calibration of the geologic time scale at the Mesozoic-Cenozoic boundary has been a problem in recent years. Many workers have employed various research techniques to establish this date and an analytical limit to the accurate determination of this boundary is now being approached. Differences in dates given by the various investigators arise from both stratigraphic and analytical uncertainties. The original definition of the boundary was a lithologic one, based on chalk. However, each correlative biostratigraphic interpretation varies with the fossil group used. Conversely, K-Ar, U-Pb and Rb-Sr geochronologic dates have to be rationalised and calibrated with each other for time scale purposes. A brief review of the current time scale evaluation by various scholars follows.

Holmes (1960) has accepted 70 million years as the date for the end of the Cretaceous Period in his revised time scale. More recent evidence suggests that Holmes' time scale needs to be changed again.

Evernden, Kistler and Curtis (1959) suggested a Cenozoic time scale based on the K-Ar dates on biotite, sanidine and glass from ash beds and glauconite from continental rocks from western United States. They suggested that the base of Paleocene is 60 m.y. old. However, in 1961, they revised their time scale and placed the Cretaceous-Tertiary boundary at 67 m.y. They have not clearly defined the bases for proposing this significantly older radiometric age.

Folinsbee, Baadsgaard and Lipson (1960) dated the uppermost Cretaceous by concordant K-Ar dating on cogenetic biotite and sanidine. They placed the Cretaceous-Tertiary boundary at 63 m.y. The extinction of Triceratops, the last known Ceratopsian dinosaur, marks the end of the Mesozoic Era. The beginning of the Triceratops Zone in Alberta is marked by the Kneehills Tuff zone and its associated bentonites (Sternberg, 1947). Folinsbee, et al. (1962), dated the Kneehills Tuff at 66 m.y. They dated a bentonite in the "Z" Coal of the basal Fort Union

Formation, Hell Creek, Montana directly overlying the last and most abundant Lance (= Hell Creek = ?Maestrichtian) dinosaur remains at 62.7 m.y. by sanidine and 61 m.y. by biotite. The sanidine date is probably the more reliable and the accepted one.

Kulp (1960) placed the base of the Paleocene at 70 m.y. However, he compiled all the geologic and geochronometric data available up to early 1961. From this, Kulp (1961) redefined the Mesozoic-Cenozoic boundary as being 63 m.y. Since the data presented in this paper were collected and compared from various laboratories in different parts of the world, Kulp's time scale is the best presently available.

CRETACEOUS-TERTIARY BOUNDARY IN ALBERTA

Stratigraphy

The Cretaceous-Tertiary boundary in Alberta was arbitrarily defined by Tyrrell (1887) as the contact between the Edmonton and Paskapoo Formations, but its actual position is controversial. Allan and Sanderson (1945) considered this contact to be disconformable. Campbell (1962) considered it to be conformable. On the other hand, Rutherford (1947), Russell (1950), Tozer (1953), Ower (1958), and Elliot (1958) thought it to be conformable at some places and disconformable elsewhere. Scanty vertebrate and fresh water paleontological evidence has made stratigraphic interpretation difficult.

More than 10,000 feet of non-marine sandstone and shale of uppermost Cretaceous and Paleocene age were deposited in southwestern Alberta on the youngest marine Cretaceous formation, the Bearpaw Shale of upper Campanian age (Tozer, 1953). Thickest remnants of these sediments now occupy the Alberta

Syncline and were derived from older sediments of the Cordilleran region to the west. Their influx was rapid and the non-marine sediments grade from coarse sandstone in the west to shale in the east.

Tyrrell (1887) named the two formations which are recognised in Central Alberta - the Edmonton (Cretaceous) and the Paskapoo (Paleocene). The Edmonton Formation consists predominantly of stratigraphically complex interfingering lenses of fine-grained bentonitic sandstone, sandy shale, carbonaceous shale and coal. Bentonitic material is conspicuous throughout the formation. The upper Edmonton is correlative with the Willow Creek Formation in southern Alberta, the Battle and Frenchman Formations of the Cypress Hills and the Hell Creek Formation of Montana and Wyoming.

The Paskapoo Formation consists of grey to yellowish brown weathering sandstone usually thick bedded but often showing false bedding and including greenish shales. The basal Paskapoo is a massive, buff-weathering uniform grey sandstone. The Edmonton Formation is easily distinguished from the overlying Paskapoo by its grey to white colour, finer grain size and higher content of argillaceous, bentonitic and carbonaceous beds.

Volcanic activity in the Cordillera of western North America was responsible for bentonitic sediments in Alberta. One such bentonitic interval, the Kneehills Tuff zone, 20 to 40 feet in thickness, is widespread and traceable for a distance of about 700 miles across southern and central Alberta. It is the stratigraphic equivalent of the Battle Formation of the Cypress Hills and part of the Colgate Member of the Fox Hills Formation in Wyoming. The Kneehills Tuff proper, about 6 inches thick forms a stratigraphic marker and correlative horizon in a sequence otherwise devoid of marker beds, and divides the Edmonton Formation into upper and lower members. In the Red Deer valley of central Alberta,

the Upper Edmonton Member is of variable thickness up to 400 feet. It contains some dinosaurian remains and is overlain by Paleocene beds. Table 1 shows a generalized correlation of uppermost Cretaceous-Tertiary formations in Alberta, modified after Tozer (1956).

Previous Investigations



Allan and Sanderson (1945) made detailed studies along the Red Deer valley in central Alberta. They postulated an erosional unconformity between the Edmonton and Paskapoo Formations with up to 450 feet of Edmonton Formation removed in some areas.

Sternberg (1947) studied the dinosaurian fauna of central Alberta. He stated that the presence of Triceratops, Tyrannosaurus, Thescelosaurus and Ankylosaurus in the Upper Edmonton Member, i.e. above the Kneehills Tuff, shows that this part of the formation is conclusively of Maestrichtian age, i.e. Hell Creek equivalent of northwestern interior of the United States (Jeletzky, 1960, 1962; Spieker, 1960; Clemens, 1960).

Russell (1950) and Tozer (1953) described the Cretaceous-Tertiary boundary in southwestern Alberta as contained within the continuous non-marine sedimentation of the Willow Creek Formation. Northward, the contact is disconformable, and in central Alberta, both lower and middle Paleocene are missing. However, on the basis of fossil mammalian remains near Calgary, Russell (1957) showed that at least a part of the basal Paskapoo is of middle Paleocene age.

From subsurface and outcrop data on the Edmonton Formation, Ower (1953) placed the Kneehills Tuff zone as the marker between Lance and pre-Lance sediments. He did not find any evidence of irregular differential erosion between

Table 1
Correlation of Uppermost Cretaceous and Paleocene Formations of Alberta

	STAGES	WESTERN UNITED STATES	CYPRESS HILLS After Russell (1950)	CENTRAL AND SOUTHERN ALBERTA PLAINS	CENTRAL ALBERTA FOOTHILLS
PALEOCENE	DANIAN	FORT UNION	RAVENSCRAG	PASKAPOO	PASKAPOO
					
UPPER CRETACEOUS	MAESTRICHTIAN (RESTRICTED)	HELL CREEK =(LANCE)	FRENCHMAN	UPPER EDMONTON	BRAZEAU
		FOX HILLS		KNEEHILLS TUFF BATTLE	
			WHITEMUD	LOWER EDMONTON	
			EASTEND		

Edmonton and overlying Paskapoo Formation. However, he assumed that there may be a disconformity between the two formations due to truncation of the uppermost Edmonton beds in an easterly direction prior to the deposition of the Paskapoo sandstones.

Subsurface correlation of the Edmonton Formation by Elliot (1958) showed that the Kneehills Tuff zone has a constant dip from central Alberta to the Foothills and that the Alberta Syncline is a westward dipping homocline at depth. There is a continuous wedge of sediments of intermediate age above the Kneehills and below the Paskapoo. Paskapoo sands overlap the wedge and cover the Edmonton Formation.

Campbell (1962) examined the boundaries of the Edmonton Formation in the Red Deer Valley in central Alberta. He concluded that the lithologic contrast between the grey- to white-coloured Edmonton Sandstone and the coarser grained massive buff weathering Paskapoo Sandstone is due to change in facies. He also concluded that the Edmonton-Paskapoo contact is transitional and highly diachronous and is located in a complex of interbedded deltaic sediments. Campbell suggested the probability of some local channel disconformities. He (personal communication) also notes a change in megaspore flora at the Kneehills Tuff zone although the lithology is not appreciably different above and below it.

Methods

For the purposes of the present investigation, 20 bentonite samples were collected between Whitecourt (54°10'N, 115°40'W) and the Cypress Hills (49°39'N, 110°30'W). Different size fractions of biotite, and in some cases sanidine, were dated by the K-Ar method. Quantitative and qualitative analysis of the clay

fraction of these bentonites was carried out to determine the nature of clay minerals. An X-ray spectrochemical method was used to determine the relative quantities of Al, Si, Ca, K, Fe, Ti, Mn, Rb, Sr, Zn, and Zr in the whole samples and in the clay fractions.

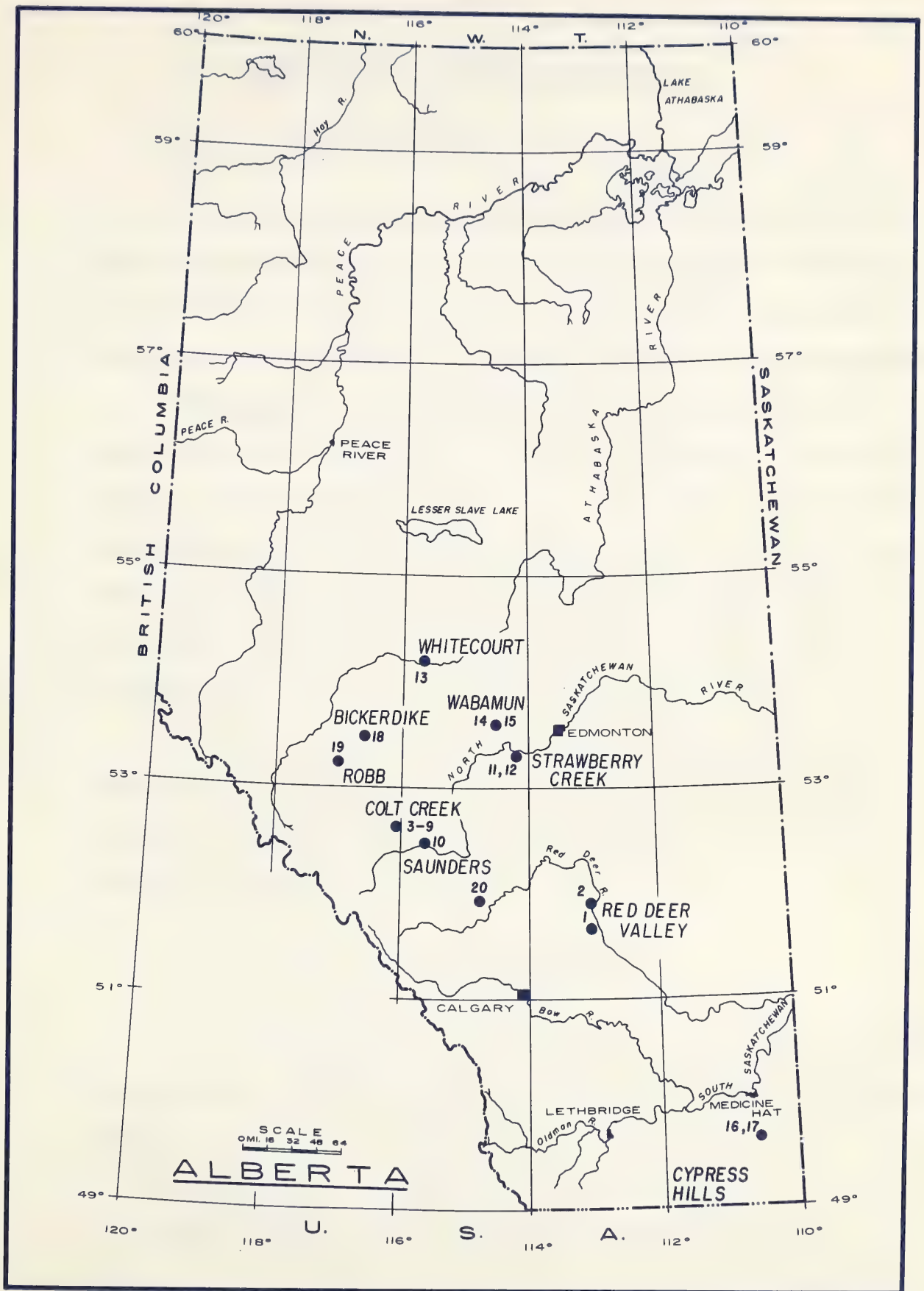


Figure 1. Location map for bentonite samples

RADIOMETRIC DATING BY K-AR METHOD

BENTONITE AS A KEY

Bentonite is exceptional as a time-stratigraphic marker. It is especially useful in sequences where fossil evidence is sparse and correlations are difficult. Bentonite beds are widespread and continuous even though thin, and occasionally may be traced and recognised over wide areas by distinctive colour and composition.

The passage of latest Cretaceous to earliest Tertiary time in Alberta is represented by essentially non-marine poorly fossiliferous strata not amenable to precise paleontologic dating. These strata are characterised by an abundance of coal with bentonitic interbeds. The K-Ar method of radiometric dating (Holmes, 1962) was undertaken with the hope that it would supply additional evidence on the boundary problem by ascertaining the time of volcanic eruption responsible for the ash beds and thus calibrate the boundary in terms of radiometric dates.

The K-Ar method has been evaluated critically with reference to the important factors introducing error in the dates. Finally, an attempt has been made to analyse and correlate the calculated dates with respect to stratigraphic sequence and geologic history of the area.

EVALUATION OF THE K-AR METHOD

The accuracy of the potassium-argon method of radiometric dating depends on the fulfilment of the following fundamental requirements, modified after Rankama (1954, p. 110).

1. The rate of decay of the radioactive nuclide must be known.
2. Sampling must be representative of the rock or mineral to be dated.

3. Analytical measurements must be sufficiently sensitive and accurate.
4. There should not be any daughter nuclide or intermediate initially present in the phase to be dated. If present, amount of such contaminant must be determined.
5. There should not be any gain or loss of the parent or daughter after the phase has formed a closed system.
6. If ionic abundance ratios are used, relative isotopic composition of the element in question must be everywhere the same in the earth's crust.

1. Decay Scheme

K^{40} , which occurs in natural potassium, decays by beta decay to Ca^{40} , or alternatively by K-capture to an excited state of Ar^{40} and by subsequent de-excitation to Ar^{40} by gamma radiation according to the following scheme:

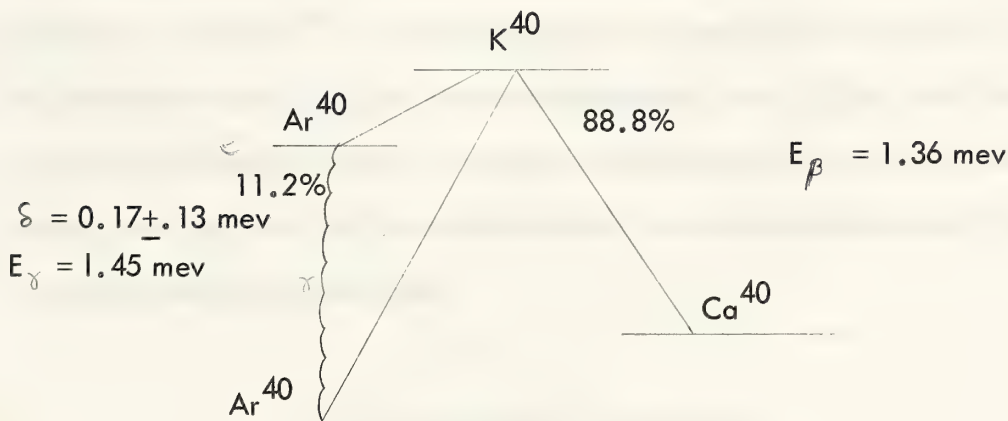


Figure 2. Decay scheme for K^{40}

The branching ratio strongly favours the beta-decay of K^{40} , but the K-Ca decay has not been used to any great extent as a chronometer because of the abundance of Ca^{40} in nature. The disintegration of K^{40} to Ar^{40} is the basis of K-Ar method of radiometric dating.

The constants used for the calculation of dates are:

$$\lambda_e = 0.589 \times 10^{-10}/\text{yr.}$$

$$\lambda_\beta = 4.76 \times 10^{-10}/\text{yr.}$$

$$K^{40}/K = 0.01181 \text{ atomic per cent}$$

However, many workers in the United States and Canada use slightly different constants:

$$\lambda_e = 0.585 \times 10^{-10}/\text{yr.}$$

$$\lambda_\beta = 4.72 \times 10^{-10}/\text{yr.}$$

$$K^{40}/K = 0.0119 \text{ atomic per cent}$$

The differences in the two sets of decay constants is due to difference in isotopic abundance used for K^{40} . This may cause some apparent confusion, but in fact, the differences cancel out and affect the date only very slightly (less than one-tenth of the analytical error). As more reliable decay constants are determined, the accumulated data can be recalculated but the relative difference in the dates will remain essentially the same.

2. Representative Sampling

Sampling must be representative of the rock or mineral to be dated. Otherwise, the calculated date will not be reasonably accurate.

Sampling for dating is always a problem and depends on the geological field conditions. The decision as to whether a particular bed is actually representative of the phase to be dated, or instead, represents a modified phase is

often arbitrary. Likewise, the stratigraphic assignment of a bed often carries personal bias.

For this work, cream coloured plastic bentonites, collected without contamination from overlying and underlying beds fulfilled the requirements of sampling to the fullest possible extent. In the case of a thin bentonite, the overlying beds from a suitable area were removed to collect clean fresh bentonite. There may be a spectrum of compositional levels in a thick bed, and in this case the sample was taken from the whole vertical thickness. Sample 494I (Bickerdike) is the only exception. The top of the 8 feet bentonite bed (Byrne, 1959) almost coincided with the water level of the river. The sample was mined 2 to 3 feet below the water level.

A pure monomineralic phase gives the best sample for dating. Pure biotite was obtained using the Frantz isodynamic magnetic separator at critical amperage and geometric settings. Some biotite separates were washed with water and acetone to remove adhering fine material. Pure sanidine was obtained from the non-magnetic fraction by careful gravity separation and acid washing. The principal cause of uncertainty in dating the biotite and sanidine separates is the presence of older or younger materials either as detrital contaminants or subsequent alteration products from the ash. (Bentonite forms by devitrification and alteration of volcanic ash and glass.)

3,4. Analytical Measurements

Analytical measurements must be sufficiently sensitive and accurate.

There should not be any daughter or intermediate initially present in the phase to be dated. If present, amount of such contaminant must be determined.

These two fundamental requirements are interdependent in the precise analyses of parent and daughter elements.

The following paragraphs give the general analytical procedures, factors controlling accuracy of the analyses and evaluation of each factor in terms of probable variation in date.

General Analytical Procedure

Mr. A. Stelmach, chemist-technician of the Rock Analysis laboratory at the University of Alberta, made potassium determinations by the gravimetric method using sodium tetraphenol boron $[\text{NaB}(\text{C}_6\text{H}_5)_4]$ as described by Wittig and Raff (1951). Rubidium was determined in the tetraphenol precipitate by X-ray fluorescence.

Ar^{40} in the sample was extracted and purified by the flux-fusion technique described by Goldich, et al. (1961). Compared to biotite, sanidine is harder to separate but easier to run in the potassium-argon train. Some biotite samples are very gassy and tend to "spray" during outgassing and torching. Preliminary baking at a temperature between 100°C and 150°C for a day reduces spraying as well as the amount of air-argon contamination in the isotopic composition of the extracted argon.

Dr. H. Baadsgaard and the writer analysed the extracted argon on a 60° Nier type mass spectrometer. The samples were analysed under both static and dynamic conditions in order to evaluate mass fractionation in the mass spectrometer, to determine precisely the amount of air argon and to increase accuracy. Under ideal conditions, data computed from both the static and dynamic runs should be the same and data agreeing to within one per cent was generally obtained.

Analytical Precision

Any calculated date depends on the $\text{Ar}^{40}/\text{K}^{40}$ ratio. Hence accuracy of both the potassium and argon analyses control the precision of the date. Important factors introducing error and thus affecting a date are as follows:

K-analysis

Though present as a major constituent in most of the datable minerals and rocks, potassium cannot be analysed as accurately as argon which is present in trace amounts (Pinson, 1961). Hurley, et al. (1961) indicated that replicate determinations by 12 different laboratories on the same MIT biotite show a poor degree of precision. The values range from 7.4 to 7.8 per cent potassium. This range of about 6 per cent is due to different methods and techniques used by different analysts, but may also reflect some variation in the sample material. The uncertainties in K-determination directly affect the $\text{Ar}^{40}/\text{K}^{40}$ ratio and hence the date. The logarithmic function of the date formula reduces the magnitude of variation. For example, 10 per cent uncertainty in $\text{Ar}^{40}/\text{K}^{40}$ ratio amounts to only 6 per cent uncertainty in the calculated date. However, replicate determinations by the same analyst using the same method are usually in good agreement. Eight replicate K-determinations on a sample at the Rock Analysis Laboratory of the University of Alberta show a mean deviation of one per cent (Baadsgaard, personal communication). Hence, it is probable that uncertainties in K-determinations cause a maximum of one to two per cent variation in the calculated dates.

Ar-analysis

Both interlaboratory and individual laboratory determinations show that argon can be measured with much more certainty than potassium. Hurley, et al. (1961) noted that the nine values reported on MIT standard biotite range from

3.81 to 3.95×10^{-4} cc/gm Ar^{40} at STP. The mean is 3.88×10^{-4} cc/gm and the maximum deviation is only 3 per cent. The value obtained at Rock Analysis Laboratory, University of Alberta, is 3.86×10^{-4} cc/gm. The important factors responsible for the variation in argon analyses are as follows:

- i) Spike calibration
- ii) Spraying of the sample, incomplete recovery or both
- iii) Final isotopic measurement
- iv) Isotope fractionation in gas transfer procedure (in mass spectrometer).

i) Spike Calibration

Ar^{38} spike is used in isotope dilution analysis. Any deviation arising from spike calibration is directly transferred to $\text{Ar}^{40}/\text{K}^{40}$ ratio and hence is critical. The spike argon used in this work was obtained from Brookhaven National Laboratory, New York. Use of 99 per cent pure Ar^{38} as is currently available from the Physikalisch-chemisches Institut, Universitat Zurich, Switzerland, should reduce the uncertainties arising from spike to some extent. Table 2 shows a comparative isotope analysis of argon from the two sources.

Table 2
Isotopic Analysis of Spike-Argon

Argon isotope	Brookhaven Natl. Lab.	Physikalisch-chemische Institute
Ar^{36}	0.015	0.003
Ar^{38}	95.3	99.982
Ar^{39}	~ 3	--
Ar^{40}	1.68	0.015

Goldich, et al. (1961) indicated that the probable error due to spike calibration is 1.3 per cent. Spikes used in this work were calibrated quadruply by Dr. H. Baadsgaard and the values obtained by different methods show a deviation of 0.3 to 0.7 per cent. Absolute values are probably within these limits.

The isotopic composition of spike argon used is

$$\left. \begin{array}{l} \text{Ar}^{36}/\text{Ar}^{38} = 0.00034 \\ \text{Ar}^{40}/\text{Ar}^{38} = 0.075 \end{array} \right\} \pm 6 \text{ per cent}$$

It is likely that the maximum error due to spike calibration and correction is 0.6 per cent.

ii) Incomplete Recovery of Argon

The second factor is concerned with the incomplete release or recovery of all the argon from the mineral or rock to be dated at the time of fusion. This may be due to spraying of the sample at the time of outgassing or torching at the beginning of fusion or incomplete fusion. It is difficult to assess the amount of argon released by the mineral under such conditions. However, in all cases of spraying, the recovered sample was treated with acid (HCl), weighed and deducted from the original sample weight. However, if spraying constitutes more than 10 per cent of the sample, the individual runs will give erratic dates (Baadsgaard, personal communication).

iii) Isotope ratio measurement

The argon isotope masses recorded on the strip chart are 36, 38 and 40 and contain argon from four sources; viz. the mineral, the spike, any argon that may have been present in the extraction train during extraction, and in the mass spectrometer (memory effect). The amount of Ar^{40} generated in the mineral due

to radioactive decay of K^{40} is of critical importance in K-Ar dating and must be precisely obtained by eliminating or subtracting the contributions from other sources. Any deviation in mass spectrometer isotope ratio measurement directly adds to error in the date. The error in isotope ratio measurement may approximate one per cent (Goldich, et al., 1961), though 1-2 parts per thousand is possible with a carefully calibrated recorder.

Ar^{40} was measured (isotope dilution method) by adding a known amount of Ar^{38} to the system during extraction and determining the Ar^{38}/Ar^{40} ratio. Elimination of contributions to Ar^{40} and Ar^{38} from different sources are as follows:

$$Ar^{40}_{\text{radiogenic}} = Ar^{40}_{\text{total}} - (Ar^{40}_{\text{spike}} + Ar^{40}_{\text{air}} + Ar^{40}_{\text{residual}})$$

$$Ar^{38}_{\text{spike}} = Ar^{38}_{\text{total}} - (Ar^{38}_{\text{air}} + Ar^{38}_{\text{residual}})$$

$$Ar^{36}_{\text{air}} = Ar^{36}_{\text{total}} - (Ar^{36}_{\text{spike}} + Ar^{36}_{\text{residual}})$$

The residual blank was determined prior to each sample run in the mass spectrometer, i.e. a scan was made over the mass 36 to 40 region to get spectrum of each argon isotope. The sample was not run until the residual peaks were small.

Because Ar^{38} constitutes only 0.063 atomic per cent air argon, Ar^{38} correction for air is almost always negligible. Ar^{38} was corrected by subtracting residual Ar^{38} from the total Ar^{38} recorded on the strip chart.

The spike argon contained some Ar^{40} and Ar^{36} and their contributions were calculated using the spike correction factors.

$$Ar^{40}_{\text{spike}} = Ar^{38}_{\text{spike}} \times (Ar^{40}/Ar^{38})_{\text{spike}} = Ar^{38}_{\text{spike}} \times 0.075$$

$$Ar^{36}_{\text{spike}} = Ar^{38}_{\text{spike}} \times (Ar^{36}/Ar^{38})_{\text{spike}} = Ar^{38}_{\text{spike}} \times 0.00034$$

Air argon contamination is a critical source of uncertainty in the amount of radiogenic argon because Ar^{40} is the most abundant argon isotope in the atmospheric argon (Table 3).

Table 3
Composition of Atmospheric Argon

Isotope	Atomic per cent
Ar ³⁶	0.337
Ar ³⁸	0.063
Ar ⁴⁰	99.6

Any error in Ar³⁶ peak measurement is transferred to Ar⁴⁰ value by a multiplication factor of about 300, so it is essential to measure Ar³⁶ with great precision. The mass spectrometer is about 100 times more sensitive under static vacuum conditions than under dynamic conditions and can measure up to 10^{-10} cc argon at STP. Hence the isotopic composition of the extracted sample was measured both under static and dynamic conditions. The air correction from large static Ar³⁶ peak was used for dynamic air correction and the dates reported are the mean of static and dynamic isotope ratio measurements.

The mass discrimination of the mass spectrometer was checked by discrimination runs using standard air argon. The Ar⁴⁰/Ar³⁶ ratio obtained was slightly different than the true value of 295.5 and was about 300 for dynamic runs and about 290 for static runs. Hence a correction factor had to be used.

$$\text{Ar}_{\text{air}}^{40} = \text{Ar}_{\text{air}}^{36} \times (\text{Ar}^{40}/\text{Ar}^{36})_{\text{air}} = \text{Ar}_{\text{air}}^{36} \times (\text{about } 300 \text{ or } 290)$$

After all the contributions from different sources are eliminated, Ar³⁸/Ar⁴⁰ ratio is calculated for each sample and multiplied by mass discrimination factor to give true Ar³⁸/Ar⁴⁰ ratio. The volume of radiogenic Ar⁴⁰ is calculated as follows:

$$\text{Ar}_{\text{ccSTP/gm}}^{40} = \frac{\text{cc STP Ar}_{(\text{spike})}^{38}}{\text{gram sample} \times \text{Ar}^{38}/\text{Ar}^{40} \text{ (calculated as above)}}$$

Air argon contamination reduces the precision of date and Hurley, et al. (1961) indicate that 30 per cent air argon contamination gives a 3 per cent deviation. However, when all the error introducing factors are taken into consideration, 30 per cent air argon contamination accounts for a maximum of 5 per cent variation in a date (Baadsgaard, et al., 1957). With the increase in air argon contamination, the error increases. Dates from samples with less than 30 per cent radiogenic argon are not reliable and may vary as much as 150 per cent for dynamic runs (Baadsgaard, personal communication). For example, the biotite date from bentonite at Bryan Mountain coal pit with 25 per cent radiogenic argon gives a date of 22.2 m.y. The bentonite is stratigraphically equivalent to Colt Creek section (Folinsbee, personal communication) which gives dates around 60 m.y. However, the effect of air argon contamination on individual dates of the nine determinations on Strawberry Creek sample does not show much scatter except in one case (Table 4).

The maximum error of most of the dates reported here is of the order of 3 to 5 per cent (Table 10). However, some samples contain less than 70 per cent radiogenic argon, therefore, the probable error is larger in those samples.

The investigation indicated that under identical conditions, weathered biotites and biotites with low potassium content (no matter whether fresh or weathered) generally give smaller proportions of radiogenic argon. In such cases, outgassing for several days, thorough torching 3 to 5 times and use of a small argon spike ensures higher radiogenic argon in the extracted sample and a reasonably accurate date.

Table 4

Effect of Air Argon Contamination on K-Ar Date

	Sample No.	Sample Location	Mineral	Percentage of radio-genic argon		
				100-70	70-30	30-10
				Date in m.y.	Date in m.y.	Date in m.y.
Paleo-cene	4941	Bickerdike	Biotite	55.6	55.7	
	4872	Colt Creek	"	58.7 59.6 59.8		
	4869	" "	"	59.3 61.5	60.0	
	4859	" "	"		61.1	59.9
Creta-ceous	4983	Z-coal	Sanidine	64.4	61.1	
	4743	Upper Ardley Coal	Biotite	49.2	52.9	51.5
	3058	Strawberry Creek	Sanidine	66.0 66.2 67.7		64.0
	4934	"	Biotite		65.4	40.2 65.7 66.8 68.2

5. Retentivity of Argon

That there must not be any gain or loss of the parent or daughter nuclide after the phase has formed a closed system is the fifth fundamental requirement in the K-Ar dating.

Any loss of argon from the mineral system or contamination from other sources introduces error. Important factors affecting this fundamental requirement in bentonites are weathering and grain size.

The use of separates of biotite and sanidine from bentonite in K-Ar dating is founded on two basic assumptions:

- (a) The datable minerals, which formed in the magma chamber or vent essentially at the time of volcanic eruption, were carried and deposited along with the volcanic dust. The difference between the time of crystal formation and ash deposition is geologically insignificant.
- (b) These minerals have not been altered or contaminated since their formation to upset the geochronometer set into operation at the time of volcanic activity.

The biotite and sanidine dates from the plastic bentonites in Alberta should be reliable, since they have not been buried deeply or significantly heated subsequent to their deposition.

Sanidine (high temperature K-feldspar) retains argon and has been proved useful in dating bentonite beds (Folinsbee, et al., 1960; Evernden, et al., 1960; Baadsgaard, et al., 1961). Sanidine has high potassium content, distinctive optical properties and can be separated from other minerals in the sand fraction of bentonite by reason of its low specific gravity. High temperature sanidine has a small optic angle. If exsolution occurs through slow cooling or diagenetic change, high sanidine structure will give away to an orthoclase structure (Folinsbee, et al.,

in press). Anorthoclase, orthoclase and microcline have large optic angles. Some of the samples separated contained the latter minerals and were not datable because they leak argon.

Biotite under static conditions retains argon and is a good geochronometer (Goldich, et al., 1961). However, Folinsbee, et al. (in press) have shown that biotite dates are somewhat lower than the cogenetic sanidine dates. The following table shows variations in the calculated dates on cogenetic biotite and sanidine from uppermost Cretaceous and Paleocene bentonites. The runs with less than 40 per cent radiogenic argon have not been included. The relatively large difference between the two mineral dates for the upper Ardley sample is due to probable loss of argon, the reason for which is not known.

Table 5

Radiometric age on cogenetic biotite and sanidine

Sample Location	Radiometric age in m.y.	
	Biotite	Sanidine
Z-coal	60.7	62.7 (64.4, 61.1)
Upper Ardley Coal	51.2 (52.9, 51.5, 49.2)	63.0
Pembina Coal White-court	62.8	64.4
Strawberry Creek	65.4	66.6 (67.7, 66.2, 66.0)

Effect of Weathering and grain size on K-Ar date

Compared to biotite in plutonic rocks, biotite in bentonite is easily weathered. Weathering begins with the replacement of K^+ by water in the crystal lattice and oxidation of Fe^{+2} without destroying the flakes (Walker, 1949). With more substitution of K^+ by water and of Fe^{+2} by Mg^{+2} from percolating waters, vermiculite forms. Weathering results in increase in optic angle, decrease in refractive index, and density, and change in colour to yellow or white.

Preliminary studies by the Geological Survey of Canada (Lowdon, 1961, p. 123) suggest that partial chloritisation of biotite has no effect on Ar^{40}/K^{40} ratio and hence on date. Kulp and Basset (1961) performed leaching experiments on biotite and their results show a decrease in Ar^{40}/K^{40} ratio. They concluded that argon is leached preferentially to potassium under base exchange conditions. Thus the K-Ar method gives a minimum date; the more weathered a biotite is, the younger the calculated date will be.

Apparent updating by weathering is shown in the data for the Colt Creek section (Figure 3). Those biotites most strongly altered give somewhat younger dates than the less altered biotites. K_2O/Rb_2O ratio seems to increase towards the top of the succession.

Hower, et al. (in press), found a spread in age values from 350 m.y. for the finest to 540 m.y. for the coarsest size fraction for Upper Ordovician Sylvan shale. They indicated that the calculated K-Ar date for shale is a decreasing function with decreasing particle size, with no levelling off at any particular given age. The spread is probably due to variability in the content of coarse detrital muscovite and illite which carry inherited radiogenic argon. The detrital material is responsible for older dates, whereas increased proportion of diagenetic fine-grained illite accounts for the younger date.

Figure 3
Colt Creek Section showing effect of
weathering on biotite K-Ar date

Sample No.	Stratigraphic position in feet	K-Ar date in m.y.	$\frac{K_2O}{\%}$	$\frac{K_2O}{Rb_2O}$	Characteristics
4872	1250'	59.4 (59.6, 59.8, 58.7)	5.23	241	fresh
4863	1200'	58.7	1.99	262	moderately weathered
4869	1030'	60.3 (60.0, 59.3, 61.5)	4.18	254	fairly fresh
4865	75'	55.8	1.25	131	strongly weathered
4859	45'	60.5 (61.1, 59.9)	2.87	157	slightly weathered
Paleocene	0				
Cretaceous					

Hart encountered a somewhat similar situation with metamorphic muscovite. Metamorphism expelled all radiogenic argon from the finer size grade but larger flakes retained some argon. The age spread he obtained from this investigation was between 675 m.y. and 350 m.y. (Hurley et al., 1960)

The present investigation shows that for minerals from the same source, there may be a relationship between apparent age and grain size but the difference is small. However, the finer samples may contain a considerable amount of fragments of coarser biotite. Biotite flakes separated from bentonites are variably resistant to mechanical processes and may be reduced in size during disintegration. It is believed that this effect is small. Since the finer grain sizes of biotite are generally more difficult to purify, increasing contamination (as for example, by clay particles) may also account for the slight decrease in date with decreasing grain size. Fine grained biotite weathers easily and this factor is probably responsible for the slightly younger date of the finer size grade.

Table 6 shows that different size fractions with similar K_2O content give approximately the same date within analytical error. Variations in K_2O content arising from weathering, contamination, or both, introduces error. In sample 4743, K_2O content decreases and calculated dates become progressively younger with decreasing size grade, but K_2O/Rb_2O ratio remains almost the same. This probably indicates that Rb is not leached preferentially to potassium but the argon-40 content seems to drop slightly.

Geological significance of K and Rb in biotite and sanidine

Rubidium follows K^+ during magmatic crystallisation and seldom forms an independent mineral because of its large ionic radius (Rankama and Sahama, 1950).

Table 6

Variation of dates in different size fractions of biotite

Sample No.	Sample Location	K ₂ O in per cent				K ₂ O/Rb ₂ O ratio				Date in m.y.			
		Size fraction (U.S. Std. sieve)				Size fraction				Size fraction			
		60-120	120-170	170-270	270-325	60-120	120-170	170-270	270-325	60-120	120-170	170-270	270-325
4872	Colt Creek	5.17	5.27	5.28	--	287	218	219	--	59.6	59.8	58.7	--
4869	"	4.40	3.97	4.18	--	262	261	246	--	60.0	59.3	61.5	--
4859	"	--	--	2.82	2.92	--	--	166	146	--	--	61.1	59.9
4743	Upper Ardley Coal	8.09	7.27	6.08	--	154	154	153	--	52.9	51.5	49.2	--

Ahrens (1952) indicated that K/Rb ratio for principal rocks ranges from 55 to 150 and averages 90. However, Taylor, et al., (1956) showed that K/Rb ratio around 240 is more reliable figure for igneous rocks. Rb content increases with increasing differentiation. There is a definite trend of K/Rb ratio for biotite and sanidine for different volcanic episodes. Table 7 shows the distribution of K_2O/Rb_2O ratio in biotite from Cretaceous and Paleocene bentonites. The samples are arranged in their stratigraphic positions and different size fractions of a sample reads from coarse at base to finer at top.

Particle Size Effect of K_2O/Rb_2O

There is probably little diagnostic relationship between grain size and K_2O/Rb_2O ratio. Table 8 shows that the ratio increases with decreasing grain size in the Kneehills Tuff zone and decreases with decreasing grain size in the Paleocene samples.

Biotite from the Kneehills Tuff zone has abnormally high rubidium content. Hence, K_2O/Rb_2O ratio ranging from 6.0 to 9.9 forms a correlation criterion for the identification of the horizon. Dodson and Long (1962) encountered high Rb content in biotite (K_2O/Rb_2O being 18.9 and 18.5) from the Tertiary Lundy granite, Bristol Channel, U.K. (52 ± 2 m.y.). They postulated that the granite represents either an extreme differentiate of a normal basalt magma or partial melting of the country rock. It is possible that the ash fall responsible for the Kneehills Tuff zone had a similar source.

Biotite accommodates rubidium in its lattice more easily than feldspar does because of the loosely bound sheet structure. Hence K_2O/Rb_2O ratio is

Table 7

K_2O/Rb_2O ratio in biotite in approximate stratigraphic succession

Sample No.	Ak No.	K ₂ O per cent	Rb ₂ O per cent	K ₂ O/Rb ₂ O	Mean K ₂ O/Rb ₂ O for the sample		
<u>Paleocene</u>							
4941	394	6.81	.040	170	157	Paleocene	
	411	6.84	.047	145			
4872	404	5.28	.024	219	241		
	403	5.24	.024	218			
	402	5.17	.018	287			
4863	406	1.99	.0076	262	262	Cretaceous-Tertiary Transition	
4869	409	4.18	.017	246	255		
	408	3.97	.015	261			
	407	4.40	.017	262			
4865	405	1.25	.0095	132	132		
4859	413	2.92	.020	146	156		
	412	2.82	.017	166			
4875	410	4.91	.037	133	133		
4983	317	5.12	.047	109	109		
4981	418	2.28	.022	104	106		
	419	2.16	.020	108			
<u>Cretaceous</u>							
4743	401	6.08	.040	153	154	Kneehills Tuff	
	400	7.27	.047	154			
	399	8.09	.053	154			
4936	393	3.89			9.55		
	392	4.17	.423	9.9			
	391	4.12	.447	9.2			
4934	390	3.14	.344	9.1	7.55		
	389	3.40	.449	7.6			
	388	4.18	.6997	6.0			

Table 8

K₂O/Rb₂O ratio for various grain sizes of biotite

Sample No.	Sample Location	K ₂ O per cent				Rb ₂ O per cent				K ₂ O/Rb ₂ O				
		Grain size (U.S. Std. sieve)				Grain size (U.S. Std. sieve)				Grain size (U.S. Std. sieve)				
		60-120	120-170	170-270	270-325	60-120	120-170	170-270	270-325	60-120	120-170	170-270	270-325	270-325
4934	Strawberry Creek	4.18	3.40	3.14	--	.6997	.449	.344	--	6.0	7.6	9.1	--	--
4936	White Court	4.12	4.17	3.89	--	.447	.423	--	--	9.2	9.9	--	--	--
4743	Upper Ardley	8.09	7.27	6.08	--	.053	.047	.040	--	154	154	153	--	--
4981	Bryan Mt	--	--	2.16	2.28	--	--	.020	.022	--	--	108	104	104
4859	Colt Creek	--	--	2.82	2.92	--	--	.017	.020	--	--	166	146	146
4869	"	4.40	3.97	4.18	--	.017	.015	.017	--	262	261	246	--	--
4872	"	5.17	5.24	5.28	--	.018	.024	.024	--	287	218	219	--	--

lower in biotite than in sanidine. Compared to biotite the K_2O/Rb_2O ratio is not appreciably different in sanidine of different volcanic episodes (Table 9).

Table 9
 K_2O/Rb_2O ratio in cogenetic biotite and sanidine

Sample Location	Biotite	Sanidine
Strawberry Creek	11.0	647.5
" "	7.6	524.7
Upper Ardley Coal	154.0	375.6
Z-coal	167.0	580.7

6. Isotope Fractionation

Because isotopic abundance ratios are used in the determination of K^{40} in K, the sixth and last basic requirement states that the relative isotopic composition of potassium must be everywhere the same in the earth's crust. Nier (1950) has shown that isotopic composition of potassium obtained from various sources is the same within analytical error.

INTERPRETATION AND DISCUSSION OF THE DATES

During the course of the present investigation, 26 K-Ar dates were completed and 11 were done earlier in the Department of Geology, University of Alberta from samples of the same bentonite horizons and their equivalents. Of these, 29 were on biotite and 8 on sanidine. The dates have been tabulated in Table 10. Dates from runs in which air argon contamination was greater than

Table 10

K-Ar dates from Cretaceous and Paleocene bentonite samples

Sample No.	Sample Location	K-Ar date in million years	
		Biotite	Sanidine
<u>Paleocene</u>			
4941	Bickerdike	55.2(55.6,54.7)	
4872	Colt Creek	59.4(59.6,59.8, 58.7)	
4863	" "	58.7	
4869	" "	60.3(60.0,59.3, 61.5)	
4865	" "	55.8	
4859	" "	60.5 (61.1,59.9)	
4983	Z-Coal Montana	60.7	62.7 (64.4,61.1)
4875	Saunders	55.3	
<u>Cretaceous</u>			
4743	Upper Ardley seam	51.2(52.9,51.5, 49.2)	63.0
4982	Pembina coal seam	62.8	64.4
4940	Cypress Hills		64.9
4936	Whitecourt	64.6	
4934	Strawberry Creek	66.8(68.0,65.7, 66.8)	
3058	" "	65.4	66.0(67.7,64.0, 66.0,66.2)

30 per cent have larger probable errors than those with a more favourable proportion of radiogenic argon (Table 4). Nonetheless, the values for these poorer runs agreed well with the better runs and were included in general averages.

Since the K-Ar method has a precision of 3 per cent at best, the validity of individual calculated dates in stratigraphic correlation is often open to question. However, when cogenetic sanidine is dated, the validity of the values reported here may be checked. Some of the biotite dates calculated were anomalous and have not been reported in the table. For example, one weathered biotite with 0.22 per cent K_2O gave a date of 26.5 m.y. The analytical precision of K- and Ar- determination drops markedly for such low K-samples.

Average values greatly improve reliability by minimizing the effects of erratic individual variations. Hence the average of runs on different grain sizes of the same mineral sample are used for interpretations.

Relative values are generally better when a single spike set is used for all the runs. During the present work, three different spike sets were used, depending on the amount of argon expected from the sample. For example, one particular set was used for samples less than one gram or less than 2 per cent K_2O content.

One note of warning should be mentioned. All the interpretations such as weathering effect, grain size effect, sedimentation rate and the like are based on a small number of dates and the disagreement between them is not large. Therefore it is difficult to distinguish a real change from one due to precision errors. The conclusions reached in this paper should be checked using a statistically significant number of samples and dates.

Because the Kneehills Tuff is a regionally widespread time-stratigraphic marker, we should expect the same date throughout its entire areal extent.

Samples of the Kneehills Tuff and its associated bentonites give a consistent date (Table 11). Sanidine dates are probably more reliable and the best value for the horizon is 66 ± 1.4 m.y.

Table 11
Correlation of the Kneehills Tuff horizon

Sample No.	Sample Location	Radiometric age in m.y.	
		Biotite	Sanidine
3058	Strawberry Creek	66.5(68.0, 65.7, 66.8, 65.4)	66.0(66.0, 66.2, 66.7, 64.0)
4936	Whitecourt	64.6	
4940	Cypress Hills		64.9

Bentonites associated with the Upper Ardley Coal and Saunders Coal pose real problems. These two seams are considered by many to be roughly correlative. Biotite date of 55.3 from Saunders is too young compared with sanidine date of 63 m.y. for the Upper Ardley Coal. Different size fractions of the biotite for the bentonite associated with the Ardley Coal give dates of 49 to 53 m.y. Folinsbee et al. (1960) dated the anorthoclase from the bed, but from a different locality, at 52 m.y. However, anorthoclase leaks argon and the date is too young compared to the sanidine date of 63 m.y. This difference in biotite-sanidine dates is possibly due to loss of argon from biotite but the reason for it is not known. The finer size fractions expelled more argon than the coarser particles and this may explain the spread of dates.

Cretaceous-Paleocene Contact

The extinction of the last known Ceratopsian dinosaur, Triceratops, marked the end of the Mesozoic Era. Three bentonite samples were collected from distant areas, all immediately and conformably overlying the last known Triceratops remains. The sanidine dates as shown in Table 12 cluster around 63 m.y. The discrepancy between the two sanidine dates from the Z-Coal, Montana is probably due to low analytical precision resulting from air argon contamination. However, the average value tends to cancel the erratic nature of the determinations.

The single radiometric age determination on the bentonite associated with the Pembina Coal shows a somewhat older date. This may be due to analytical error partly arising from the spike correction factor. The spike used previously had a large correction factor.

Table 12

Correlation of beds immediately overlying the Triceratops Zone

Sample No.	Sample Location	Sanidine date in m.y.	Per cent radiogenic argon
4982	Pembina Coal Whitecourt Alberta	64.4	86
4743	Upper Ardley Coal Red Deer Valley Alberta	63.0	97
4983	Z-Coal Hell Creek Montana	61.1	69
		62.7 64.4	40

With due consideration to the variation between biotite and sanidine dates (Table 5) and weathering effect (Fig. 3), it is probable that sanidine from the Colt Creek section would give dates of 62–63 m.y. It is probable that 63 ± 1 m.y. marks the end of the Mesozoic Era.

Though the coal beds at the base of the Fort Union Formation, Hell Creek, Montana, along Colt Creek, at Saunders and at Bryan Mountain, Alberta are often assigned to the early Paleocene, whereas the coal beds at Wabamun, Ardley and Whitecourt are considered to be uppermost Cretaceous, it is probable that they are lithogenetically correlative although diachronous, becoming younger to the west with shift of depositional environment (Fig. 4). It is likely that the Cretaceous passes gradationally into Paleocene without any significant stratigraphic break.

Source and Volcanic Activity

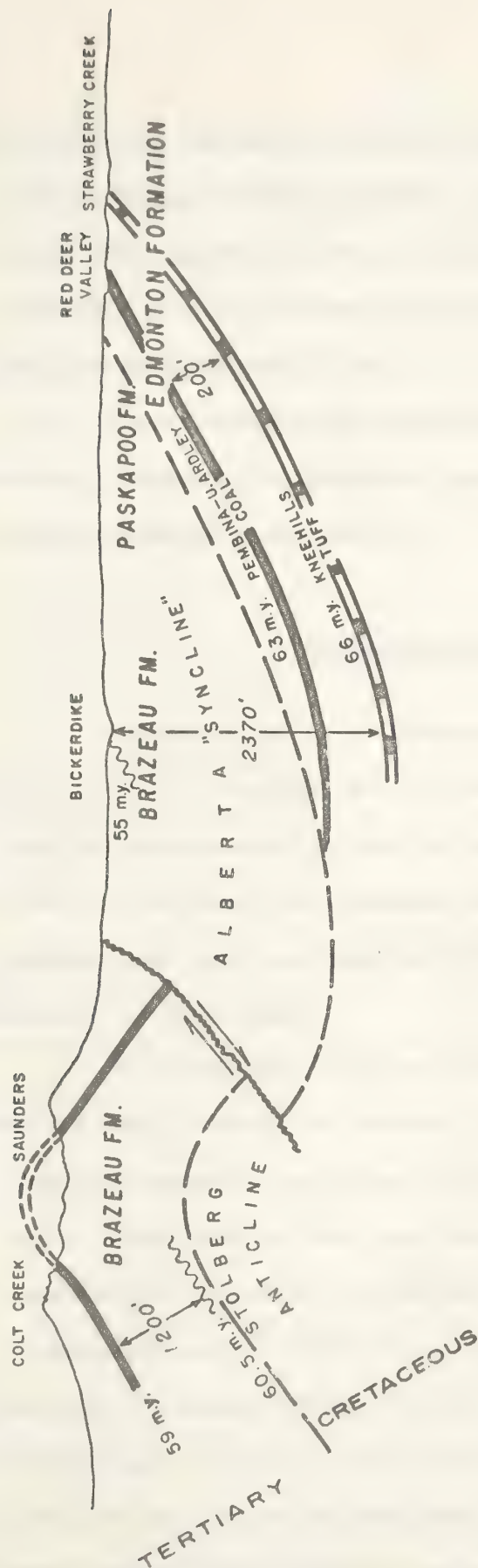
Minor element content may be useful in identifying a source for the volcanic debris. Biotite in bentonite has a relatively high resistance to weathering compared to the groundmass which has altered to montmorillonite. Biotite crystallizes early and accommodates many trace elements. By comparing these trace elements, the source might possibly be identified.

In the present study, only Rb has been determined. In the absence of large numbers of Rb values for source intrusives that might be responsible for the bentonite beds, the source cannot at present be identified. There is an interesting relationship in K_2O/Rb_2O ratios of biotite that suggests three groups of bentonite beds (Table 7, p. 29).

The first group includes the Kneehills Tuff, and its equivalent bentonites (65–66 m.y.). High Rb content and low K_2O/Rb_2O ratio is characteristic

FOOTHILLS

P L A I N S



R A T E O F S E D I M E N T A T I O N

800' / m.y.

200' / m.y.

<100' / m.y.

LEGEND

--- Cretaceous - Tertiary boundary

== Coal beds

== Kneehills Tuff

~ Bentonite

Figure 4. Diagrammatic Section Showing Relationships of Diachronous Coal Beds of Cretaceous-Tertiary Transition

of these beds. The second group of ash beds are related to the major coal beds of the Cretaceous-Tertiary transition. K_2O/Rb_2O ratio in biotite appears to increase from uppermost Cretaceous (154) to Paleocene (262). The third group (Paleocene-55 m.y.) has been inferred from two biotite determinations of a single sample (Bickerdike) (Fig. 4).

These groups probably represent three different periods of volcanic activity. However, this conclusion should be checked with statistically significant number of determinations.

Rates of Sedimentation

Because bentonites are time-stratigraphic horizons, rates of sedimentation may be calculated from the time intervals between these marker beds. The Colt Creek section would be ideal for the purpose but could not be used because of the low precision of the weathered biotite date from the base of the section. Sanidine dates, when available, will probably show a rather high rate of sedimentation for this region.

The stratigraphic thickness of 2370 feet between the Kneehills Tuff and the Bickerdike bentonite at Bickerdike (Williams, personal communication) indicates a sedimentation rate of about 200 feet per million year. In the Red Deer Valley, central Alberta, the Upper Ardley coal seam is separated from the Kneehills Tuff horizon by about 200 feet of upper Edmonton Formation, indicating a sedimentation rate of 70 ft./m.y. These rates of sedimentation are in agreement with the geologic setting of the area. Rapid sedimentation in the present Foothills region was due to influx of detritus from the rising Cordilleran region to the west into an active negative area. The sediments become somewhat finer toward the east where subsidence was less.

CONCLUSIONS

A brief summary of the results and conclusions obtained from the present study are as follows:

The Cretaceous-Tertiary boundary in Alberta is located in stratigraphically complex and lithologically diverse interfingering lenses of continental sandstone and sandy shale. The transition is marked by several thick diachronous coal beds (uppermost Cretaceous in central Alberta to lowest Paleocene in the Foothills). Sparse Ceratopsian dinosaur (Cretaceous) and mammalian (Paleocene) remains, and limited freshwater invertebrate faunas have made resolution of the boundary position difficult. Radiometric age data have not been obtained for the type boundary in Europe.

Determination of the time of deposition of bentonite interbeds by the K-Ar method of dating and incorporation of the available vertebrate paleontologic evidence place the Cretaceous-Tertiary boundary at 63 ± 1 m.y.

Sanidine dates are generally more reliable than cogenetic biotite dates for geologically young samples because it is usually possible to separate pure radiogenic argon from sanidine; in addition, there is probable loss of some argon from the sheet structure of biotite.

Weathered biotite tends to give younger dates than fresh biotite because under base exchange conditions, argon is leached preferentially to potassium; however, the K_2O/Rb_2O ratio apparently remains the same. The K_2O/Rb_2O ratio may be useful in correlation of volcanic episodes.

There may be a relationship of progressively younger radiometric age with decreasing particle size, but the difference is small.

There were probably three periods of more active volcanic activity in uppermost Cretaceous–Paleocene time responsible for the Kneehills Tuff horizon (66 ± 1.5 m.y.), bentonites associated with the coal beds of Cretaceous–Tertiary transition (63–60 m.y.) and younger Paleocene bentonites (55 ± 1.5 m.y.).

APPENDIX A

CLAY MINERALOGY OF BENTONITE

Quantitative and qualitative clay mineral analysis by the X-ray diffraction method was undertaken to characterize mineralogically the Cretaceous and Paleocene bentonites.

Identification of clays by the X-ray diffraction method is based largely on the precise determination of the basal spacing under different conditions. Variation in basal spacing in a single clay specimen is due to swelling resulting from introduction of water or polar compounds in the inter-layer positions or to shrinkage due to dehydration.

ANALYTICAL PROCEDURE

A film of less than two-micron-size oriented clay flakes was obtained on a frosted micro-slide by settling from aqueous suspension. The thickness of the clay film was not precisely controlled; however, slides too thick to pass transmitted light or too thin to produce good X-ray patterns were rejected.

Slides were mounted on a standard Norelco wide-angle diffractometer with geiger counter and subjected to Ni-filtered Cu-radiation at 35 Kv and 15 MA. The goniometer scanned at $1^{\circ} 2\theta$ per minute. To give best resolution, rate meter settings were varied, depending on the diffraction intensity of the untreated, glycolated and heat treated samples. The geiger tube pick-up was operated at 1500 volts.

X-ray patterns were obtained for each sample both before and after ethylene glycol treatment in an evacuated container (Brunton, 1955). The slides were later heated to 475°C for 12 hours in an electric furnace. The

area under each peak (d_{001}) was calculated from the diffraction pattern of the glycol expanded sample. The technique used to calculate the amount of each clay is essentially the same as the one described by Maiklem (1962).

Clays which expand to about 17 \AA upon glycolation and collapse irreversibly to about 10 \AA on heat treatment have been considered to be montmorillonite. A 7 \AA spacing may be d_{001} of kaolinite or d_{002} of iron rich chlorite or both. The two minerals are usually differentiated by the heat treatment technique which destroys the kaolinite. A breakdown of the X-ray unit prevented the running of heated diffraction patterns of all the samples. However, in the samples run, the 7 \AA peak was destroyed and thus has been attributed to kaolinite. It is present in small quantities only, and in most samples it was not identified. Illite has a basal spacing of 10 \AA which does not shift on glycolation or heat treatment, but becomes slightly sharper after heating.

In the present study, the general order of clay mineral abundance in the clay fraction is montmorillonite, illite, kaolinite. Quartz is invariably present. A 3.43 \AA is due to the presence of zeolites. Slaughter and Earley (in press) indicated that bentonite-forming processes acting on volcanic ash under different pH conditions produce montmorillonite, zeolite, kaolinite and silica. Chlorite may or may not be present. Byrne and Farvolden (1959) noted the absence of kaolinite and abundance of chlorite in some bentonites in the Cretaceous Bearpaw Formation of Alberta. Maiklem (1962) noted that mixed layer clay is a major constituent of the bentonites from the Belly River Formation of the Cretaceous.

No long spacing mixed-layer clays have been found. However, the montmorillonite may contain some mixed layer clays.

DISCUSSION OF THE MINERALOGICAL ANALYSES

The mineralogical analyses of the clays are given in Table 13. Montmorillonite is the major constituent, but some illite may be present as a mixed layer in the montmorillonite. The basal spacings given are for the glycolated samples. There is no significant variation in the clay mineral content of the Cretaceous and Paleocene samples. This may be due to alteration under similar conditions, similar parent materials, or both.

Some of the samples which flocculated readily during the separation of the clay fraction have a high CaO content (see spectrochemical analyses), and are probably Ca-bearing. Samples with a large part of clay in the colloidal suspension even after 60 hours of settling (during the preparation of oriented slides) are low in Ca and are probably Na montmorillonite. McAtee (1955) noted that larger bentonite particles preferentially adsorb polyvalent cations to form tighter layers and flocculate easily. Smaller particles attract monovalent ions like Na. Hence, Na-montmorillonite has colloidal properties.

In general, Na-montmorillonite is the swelling type and Ca-montmorillonite is the non-swelling type. Wyoming bentonite contains both Na- and Ca-montmorillonite because of differences in isomorphic substitution within the montmorillonite lattice (McAtee, 1955). The average of 45 Wyoming bentonites gave 2.01 per cent Na_2O and 1.54 per cent CaO (Short and Earley, in press). The bentonites under investigation are non-swelling types and the average of 18 clay samples show 2.21 per cent CaO. Therefore, it is probable that they are predominantly Ca-bearing.

Table 13
Mineralogical Composition of Bentonite Clays

Sample No.	d(001) in Å (glycolated)			Weight per cent		
	Montmorillonite	Illite	Kaolinite	Montmorillonite	Illite	Kaolinite
<u>Paleocene</u>						
4859	16.75			100		
4863	16.78		7.13	87.1		12.9
4865	16.78		7.10	95.8		4.2
4869	16.72			100		
4870	16.85			100		
4941	16.72	10.15		89.9	10.1	
<u>Cretaceous</u>						
4343	16.91			100		
4737	16.94			100		
4743	16.66	10.05		83.3	16.7	
4875	17.05		7.13	86.9		3.1
4934	17.95			100		
4935	17.18			100		
4936	16.78	9.99		97.7	2.3	
4937	16.66		7.13	86.9		13.1
4938	16.66		7.03	98.5		1.5
4939	16.85	9.93		73.6	26.4	

APPENDIX B

X-RAY SPECTROCHEMICAL ANALYSIS

INTRODUCTION

The X-ray spectrochemical method is useful for comprehensive and rapid surveys of the chemical composition of rocks and minerals including a large number of trace elements ($Z > 12$), with minimum sample preparation. The bentonite samples were analysed by this non-destructive method in the hope that the variations in element distribution might throw some light on the Cretaceous-Tertiary boundary problem. The critical variants controlling the fluctuations in chemical composition of bentonite have been considered and an attempt has been made to postulate the composition of the source rock.

During volcanic eruptions, clouds of volcanic dust rise to a variable height (up to 30 miles) and later settle down to form ash beds. The distribution patterns of ash beds are strikingly similar and characterised by the development of tongue-shaped lobes. The direction of the long axis of the lobe is approximately parallel to the vector resultant wind above the volcano at the time of eruption (Eaton, 1963).

Some bentonites are layered and show poorly developed graded bedding, each layer being a different ash fall. In addition, there are geographic variations in textural and structural parameters along and transverse to the lobe axis. An inverse relationship exists between grain size and the distance from the axis of the lobe (Slaughter and Earley, in press).

The parent material contains minerals that are comparatively more resistant to weathering than glass. These include feldspars, quartz, biotite, magnetite, zircon and apatite. The feldspars are euhedral to subhedral, clear

and contain few inclusions; plagioclase predominates over the alkali feldspars. Of the alkali feldspars, sanidine (high temperature K-feldspar) is most abundant followed by orthoclase and microcline which is rare or absent. The abundance of quartz is secondary to that of the feldspars and is usually less than 10 per cent of the total sand and silt fraction (Slaughter and Earley, in press). Biotite is often common in the coarse fraction.

ANALYTICAL METHOD AND ACCURACY

All X-ray fluorescence analyses were performed on a Norelco standard X-ray spectrograph equipped with tungsten tube and digital counters. Al_2O_3 , SiO_2 , CaO and K_2O were determined with an EDDT analysing crystal, using evacuated X-ray path, flow proportion counter and pulse height analyser. TiO_2 , MnO , and Fe_2O_3 were determined with a LiF crystal and flow proportion counter whereas Rb, Sr, Zn and Zr were determined with LiF crystal and scintillation counter. Table 14 shows the operating conditions.

Calibration Procedure

Calibration curves were prepared from a series of wet-chemically analysed rock standards covering a wide range of composition. Standards are from rocks of igneous and sedimentary origin and include three bentonites, one sanidine, one syenite, one meteorite, two sills and U.S.G.S. Standard Samples Granite G-1 and Diabase W-1. Quantities of the major elements fell within the ranges of standards and hence there was no necessity of extrapolating the calibration curves.

Tablets 1 1/4 inch in diameter for the X-ray analysis were prepared by pressing a thoroughly mixed sample diluted 50:50 with borax at 15,000 psi.

Table 14
Operating Conditions for Fluorescence X-ray Spectrochemical Analysis

Element	Crystal	Peak Used	Peak Location 2θ	Back-ground 2θ	Pulse Height Analyser		Reference Tablet	X-ray path	Counter	Voltage	Total Counts
					Base Line Y	Window V					
^{13}Al	EDDT	$\text{K}_{\alpha 1} + \text{K}_{\alpha 2}$	112.40°	--	2	12	G-1	Vac.	F.P.	1500	12,800
^{14}Si	EDDT	$\text{K}_{\alpha 1} + \text{K}_{\alpha 2}$	77.72	--	2	7	G-1	Vac.	F.P.	1450	32,000
^{19}K	EDDT	$\text{K}_{\alpha 1} + \text{K}_{\alpha 2}$	19.84	--	7	12	G-1	Vac.	F.P.	1450	64,000
^{20}Ca	EDDT	$\text{K}_{\alpha 1} + \text{K}_{\alpha 2}$	14.40	--	7	10	R-24	Vac.	F.P.	1450	64,000
^{22}Ti	LiF	$\text{K}_{\alpha 1} + \text{K}_{\alpha 2}$	86.31	--	9	18	R-24	Air.	F.P.	1450	16,000
^{25}Mn	LiF	$\text{K}_{\alpha 1} + \text{K}_{\alpha 2}$	63.05	--	15	20	G-1	Air	F.P.	1450	64,000
^{26}Fe	LiF	$\text{K}_{\alpha 1} + \text{K}_{\alpha 2}$	57.56	--	--	--	G-1	Air	F.P.	1450	512,000
^{30}Zn	LiF	$\text{K}_{\alpha 1} + \text{K}_{\alpha 2}$	41.88	42.40	6	24	G-1	Air	Sci.	800	8,000
^{37}Rb	LiF	$\text{K}_{\alpha 1} + \text{K}_{\alpha 2}$	26.60	27.20	--	--	G-1	Air	Sci.	800	32,000
^{38}Sr	LiF	$\text{K}_{\alpha 1} + \text{K}_{\alpha 2}$	25.13	25.60	--	--	G-1	Air	Sci.	800	32,000
^{40}Zr	LiF	$\text{K}_{\alpha 1} + \text{K}_{\alpha 2}$	22.52	22.85	--	--	G-1	Air	Sci.	800	64,000

Details of sample preparation procedure and evaluation of errors are described in Maiklem (1962).

Precision or the degree of reproducibility can easily be evaluated, but precise determinations do not necessarily indicate correctness. None of the samples under present investigation were analysed wet-chemically or by other analytical methods. For K_2O , CaO , Fe_2O_3 , MnO and TiO_2 , the maximum variation in reproducibility is of the order of 5 per cent of the quantity present, whereas for Al_2O_3 , and SiO_2 , it is up to 15 per cent. The Department has recently developed an improved technique giving ± 10 per cent reproducibility in the determination of Al_2O_3 and SiO_2 and ± 2 per cent in some other major elements (Campbell, personal communication).

DISCUSSION AND INTERPRETATION OF DATA

Differences in chemical composition between bentonites may be a result of the variations in the modal mineral content of the rocks with or without changes in mineral assemblage, variation in the chemical composition of the constituent minerals or both. The analytical data for the Cretaceous samples are presented in Table 16 and for the Paleocene samples in Table 15; the averages are given in Table 17.

The major elements are reported in weight per cent of the oxides and the trace elements in p.p.m. of the metal. Comparative distributions of elements in the Cretaceous and Paleocene (whole samples and clay fractions) are shown by means of bar-graphs in Figures 4, 5 and 6. It appears from the limited number of samples examined that these Cretaceous and Tertiary bentonites, as groups, do not differ significantly in elemental composition.

The critical components controlling the differences in chemical composition are biotite and montmorillonite.

Table 15
X-Ray Spectrochemical Analyses of Paleocene Bentonites

SAMPLE NO.	TYPE	WEIGHT PER CENT								P. P. M.			
		SiO ₂	Al ₂ O ₃	CaO	K ₂ O	Fe ₂ O ₃	TiO ₂	MnO	Rb	Sr	Zn	Zr	
4859	W	72.5	13.9	2.81	0.86	3.89	.30	.046	54	345	57	282	
	C	57.8	17.8	3.11	0.36	5.26	.19	.070	35	345	41	206	
4863	W	50.4	18.2	2.64	0.73	5.16	.27	.023	69	180	97	334	
	C	53.9	22.5	2.17	0.75	5.26	.25	.022	69	129	97	259	
4865	W	57.4	15.7	3.22	0.29	6.08	.20	.029	30	193	149	405	
	C	54.4	18.4	2.26	0.42	5.84	.25	.027	36	174	100	539	
4869	W	56.9	17.3	1.94	1.13	6.86	.29	.018	67	105	99	339	
	C	51.8	18.2	2.07	1.22	6.69	.24	.017	75	89	103	269	
4870	W	65.6	14.2	3.26	0.59	4.63	.37	.032	38	183	74	353	
	C	58.9	16.9	2.52	0.38	6.14	.34	.027	36	151	91	374	
4871	W	61.9	16.2	3.78	0.45	3.45	.20	.035	40	581	57	310	
	C	56.1	17.5	2.57	0.37	6.27	.20	.015	43	644	63	328	
4872	W	54.3	15.8	2.73	1.30	5.84	.24	.016	82	859	66	407	
	C	54.0	16.6	2.05	1.04	6.27	.19	.011	85	821	81	331	
4941	W	65.1	13.0	2.14	0.72	3.06	.40	.049	44	844	49	366	
	C	61.9	15.1	1.70	0.35	4.80	.42	.075	43	462	63	290	

W = whole sample

C = clay fraction (<2 microns)

Table 16
X-ray Spectrochemical Analyses of Uppermost Cretaceous Bentonites

SAMPLE NO.	TYPE	WEIGHT PER CENT							P. P. M.			
		SiO ₂	Al ₂ O ₃	CaO	K ₂ O	Fe ₂ O ₃	TiO ₂	MnO	Rb	Sr	Zn	Zr
4343	W	46.9	17.0	2.70	1.74	6.57	.31	.036	79	226	103	380
	C	50.7	21.4	2.91	1.66	7.18	.41	.028	76	133	138	404
4737	W	57.9	17.7	3.12	0.39	6.77	.30	.026	40	396	70	410
	C	54.3	19.2	2.73	0.27	7.02	.30	.026	28	332	27	354
4743	W	57.8	18.8	2.22	1.51	2.80	.44	.015	68	1029	66	562
	C	53.5	18.9	2.22	0.56	3.28	.41	.015	42	402	84	206
4875	W	59.7	14.8	2.69	0.74	3.65	.40	.014	57	310	58	444
	C	49.9	17.8	2.41	0.38	4.36	.31	.016	42	310	78	354
4934	W	59.3	16.7	1.33	0.57	7.00	.46	.025	145	325	28	306
	C	57.9	19.8	1.22	0.30	7.62	.26	.023	36	306	27	192
4935	W	53.4	20.5	1.64	0.44	4.44	.32	.013	52	460	31	310
	C	56.5	21.6	1.26	0.34	4.68	.37	.012	48	362	27	240
4936	W	68.3	13.5	1.42	1.10	3.70	.51	.012	133	354	34	392
	C	59.3	17.3	1.67	0.47	6.16	.31	.014	84	381	32	257
4937	W	46.7	20.8	1.55	0.73	2.63	.32	.028	47	84	65	157
	C	41.0	22.9	2.01	0.47	3.02	.26	.026	99	88	62	112
4938	W	53.5	21.2	2.60	1.19	5.31	.54	.037	75	95	164	279
	C	47.1	21.3	2.75	1.01	5.48	.48	.025	100	92	59	271
4940	W	59.5	16.5	1.48	0.67	5.51	.38	.024	95	188	19	240

W = whole sample

C = clay fraction (2 microns)

Table 17
Chemical Composition of Bentonites

Major elements in %	Tertiary bentonites(8)		Cretaceous bentonites(10)		Total Tertiary and Cretaceous bentonites(18)	
	Whole sample	Clay	Whole sample	Clay	Whole sample	Clay
SiO ₂	60.49	56.09	56.3	52.2	58.2	54.0
Al ₂ O ₃	15.54	17.88	17.7	20.0	16.8	19.0
Fe ₂ O ₃	4.87	5.81	4.84	5.4	4.86	5.61
CaO	2.81	2.31	2.08	2.13	2.40	2.21
K ₂ O	0.76	0.61	0.91	0.61	0.84	0.61
TiO ₂	0.28	0.26	0.40	0.35	0.35	0.31
MnO	0.031	0.033	0.023	0.021	0.027	0.026
Trace elements in p.p.m.						
Rb	53	53	79	62	68	59
Sr	411	352	346	267	375	307
Zn	81	80	64	59	72	69
Zr	350	325	348	266	349	293

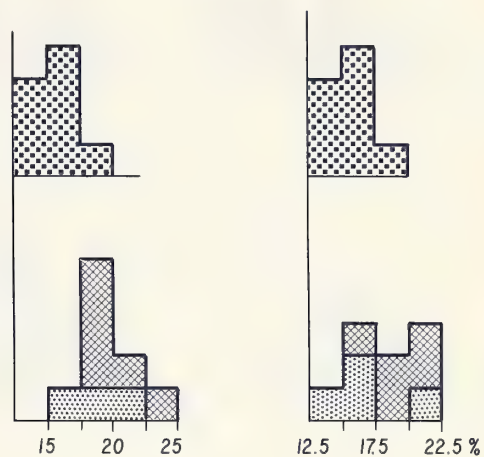
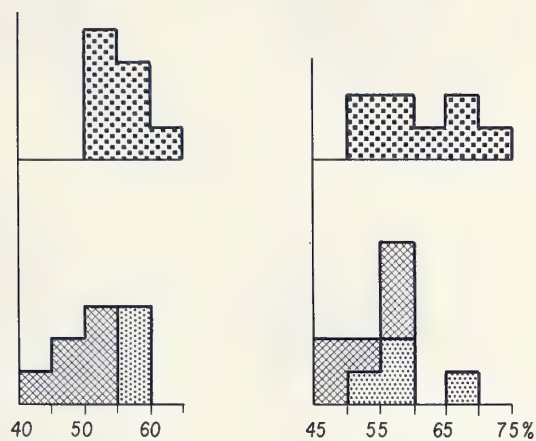
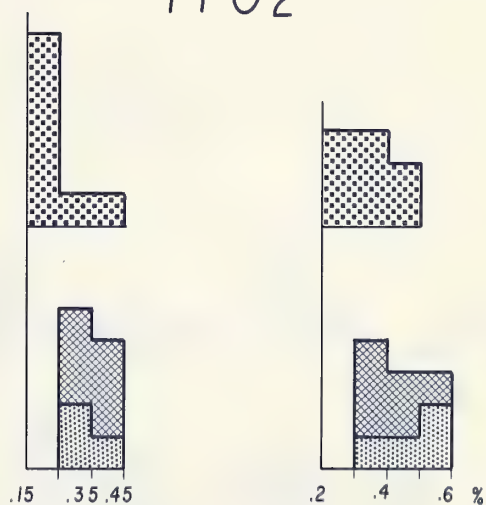
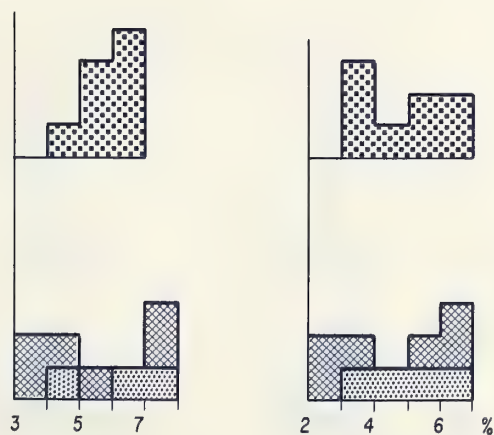
Number in the parenthesis refer to the number of samples used to calculate the average.

CLAY FRACTIONS

WHOLE SAMPLES

CLAY FRACTIONS

WHOLE SAMPLES

 SiO_2 Al_2O_3  Fe_2O_3 TiO_2 

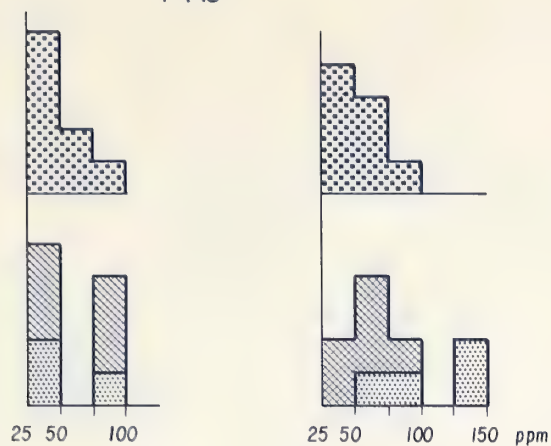
PALEOCENE

KNEEHILLS TUFF ZONE

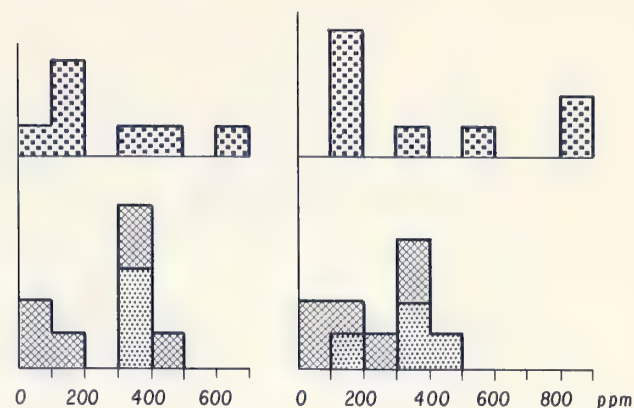
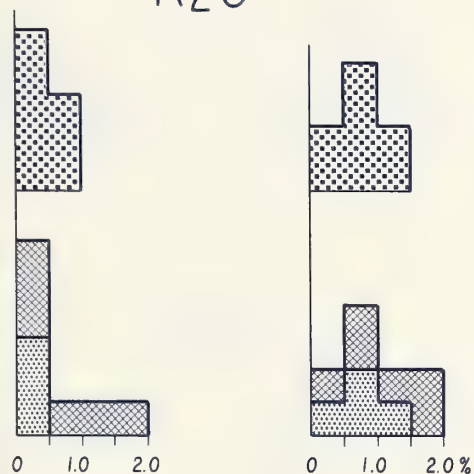
CRETACEOUS OTHER THAN KNEEHILLS TUFF ZONE

Figure 5. Distribution of SiO_2 , Al_2O_3 , Fe_2O_3 and TiO_2 in bentonite samples

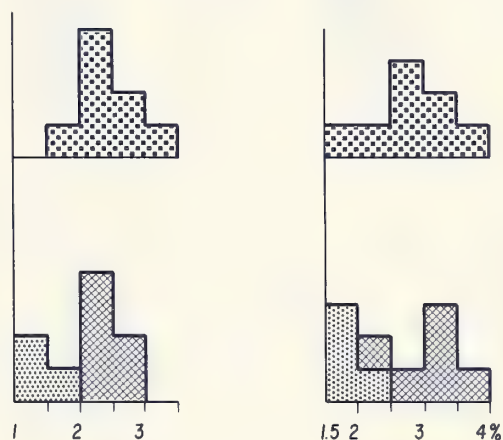
Rb



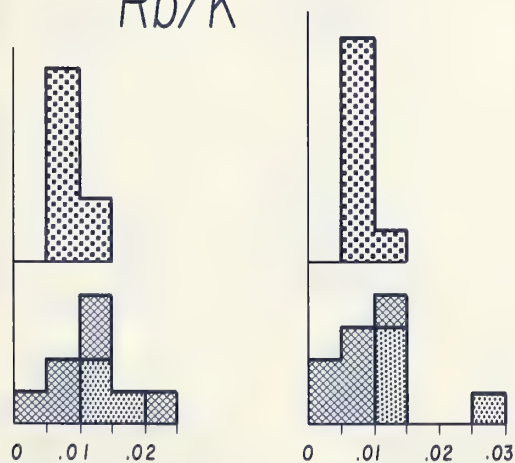
Sr

K₂O

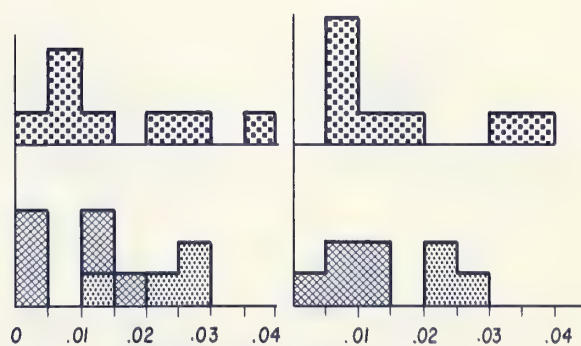
CaO



Rb/K



Sr/Ca



PALEOCENE

KNEEHILLS TUFF ZONE

CRETACEOUS OTHER THAN KNEEHILLS TUFF ZONE

Figure 6. Distribution of Rb, Sr, K₂O, CaO, Rb/K and Sr/Ca in bentonite samples

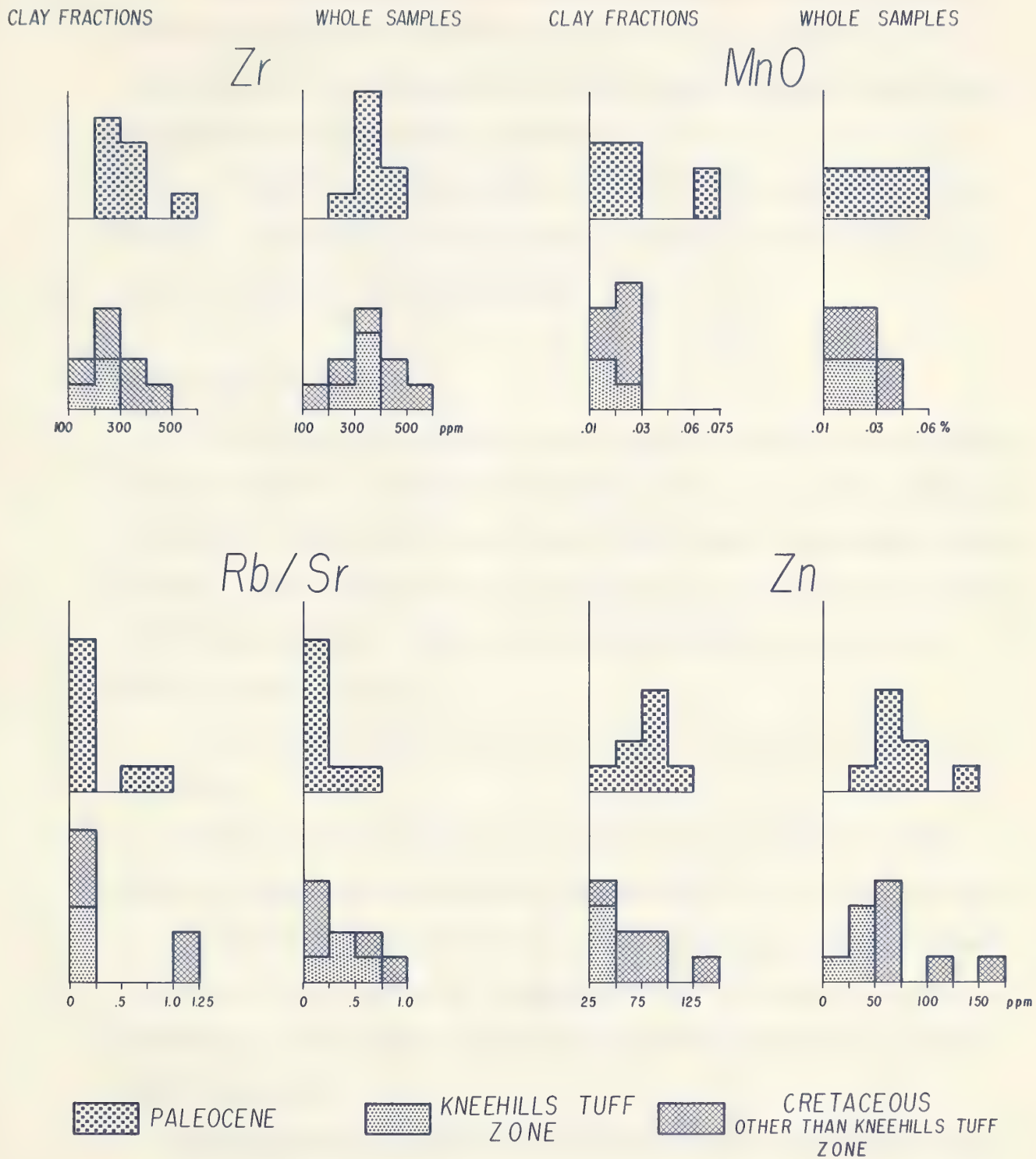


Figure 7. Distribution of MnO, Zr, Zn, and Rb/Sr in bentonite samples

Biotite comprises a small fraction of the bentonites, but accommodates in the lattice many trace elements such as Mn, Ti, Li, Cr, Ni, Rb, Cs, and Zn. The substitution of these elements in the lattice varies considerably with differences in environmental conditions of crystallization.

Montmorillonite plays a dominant role in the overall composition of the bentonite. It constitutes about three-fourths of the bulk sample and has an expandable lattice with high base exchange capacity.

POSTULATED SOURCE ROCK

It is difficult from the major element content to identify the source responsible for a bentonite. The parent material of bentonite is volcanic ash, which, due to a lobate distribution pattern, may have an initial mineral content which changes laterally. Moreover, during the course of alteration of the ash to bentonite it may have undergone important relative enrichment or depletion of certain elements (Short and Earley, in press).

Three compositional calculations are useful in identifying the source rock composition.

- a) $K + Na/Ca$ ratio or the Differentiation Index of Tuttle and Thornton (1960) could not be pursued because sodium was not determinable by the method employed.
- b) K_2O/CaO ratio (Putnam and Burnham, 1963) delineates rock types, provided undersaturated rocks or rocks with unusual minerals are not involved. Preferential release of K over Ca during alteration limits the application of the method in respect to bentonites.
- c) SiO_2/Al_2O_3 ratio was used by Short and Earley (in press) to postulate the source of the Wyoming bentonites. They indicate that the method has serious limitations in that the conversion of ash to bentonite is accompanied by enrichment of alumina

and depletion of silica. With a $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio of 2.8 for the Wyoming bentonites, they assumed the source rock to be latite. If the same analogy is applied, the source rock for the bentonites under investigation might range from latite to rhyolite, and the alteration of the ash beds probably took place under alkaline conditions. Table 18 shows $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios of some common volcanic rocks.

Table 18

$\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio of common rocks (after Short and Earley, in press)

<u>Rock type</u>	<u>$\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio</u>
Rhyolite	4.2-4.6
Trachyte	3.6-3.8
Quartz latite	3.8-4.2
Latite	3.4-3.5
Basalt	2.8-3.1
Cretaceous bentonite	3.27]
Paleocene bentonite	3.89] Present study

APPENDIX C

LOCATION AND DESCRIPTION OF BENTONITE SAMPLES

No.	Departmental No.	Location	Description and Stratigraphic Location
1	4737	Red Deer Valley NW 9-31-22-W4 51°41'N 113°05'W	4" thick bentonite bed 9' above coal, 14' above coal pit bottom, New Ghost Pine coal pit, Upper Cretaceous
2	4743	Red Deer Valley NE-NW-12-34- 22-W4, 51°55'N 113°00'W	Bentonite in Upper Ardley coal seam Upper Cretaceous
3	4859	Colt Creek Tp42-15-W5 52°38'N 116°01'W	1' bentonite 45' above mapped Edmonton- Paskapoo contact, tributary of Colt Creek, Paleocene
4	4863	Colt Creek Tp42-14-W5 52°38'N 116°01'W	6" bentonite 10' above 9' thick coal seam, 1200' above Edmonton-Paskapoo contact
5	4865	44-15-W5 52°38'N 116°01'W	75' above Edmonton-Paskapoo contact, Colt Creek, Paleocene
6	4869	Colt Creek Tp42-15-W5 52°38'N 116°01'W	1030' above Edmonton-Paskapoo contact tributary of Colt Creek, Paleocene
7	4870	as above	1' thick bentonite on the west bank of Colt Creek at the mouth of tributary 1140' above Edmonton-Paskapoo contact, Paleocene
8	4871	Colt Creek Tp42-15-W5 52°38'N 116°01'W	West bank of Colt Creek at the mouth of tributary. 1240' above Edmonton- Paskapoo contact. Paleocene
9	4872	as above	1' thick bentonite bed, west bank of Colt Creek at the mouth of tributary, 1250' above Edmonton-Paskapoo contact, Paleocene

No.	Departmental No.	Location	Description and Stratigraphic Location
10	4875	Saunders Lsd5-19-40-12-W5, 52°27.5'N, 115°43'W	11" thick bentonite in 7.5' thick coal seam in Creek, western side of railway bridge, Saunders Railway Station, Paleocene
11	4934	Strawberry Creek Lsd4-5-50-2-W5 53°17'N, 116°06'W	Dark bentonite 2-5" above lower tuff which is 6' below upper tuff, north bank of creek, Kneehills Tuff, Upper Cretaceous
12	4935	as above	Grey bentonite 6' above upper tuff, Kneehills Tuff, Upper Cretaceous
13	4936	Whitecourt Lsd3-7-60-12-W5 54°10'N, 115°40'W	6" bentonite bed above 8" tuff in black mud, 35' above river level, Kneehills Tuff, Upper Cretaceous
14	4937	Wabamun Lsd 5-14-53-4-W5 53°36'N, 114°30'W	3" bentonite in coal, Wabamun open pit coal mine, Upper Cretaceous
15	4938	as above	Bentonite, 5' above coal and 2' below Paskapoo Sandstone, Upper Cretaceous
16	4939	Cypress Hills SW21-8-4-W4 49°40'N, 110°30'W	3-5' thick bentonitic clay, quarry in Frenchman Formation, Cretaceous
17	4940	Cypress Hills Lsd 15-16-9-8-4- W4, 49°39'N 110°30'W	Khaki bentonite 1' to 15" thick above 8" tuff. Quarry 45, Battle Formation, Kneehills Tuff, Upper Cretaceous
18	4941	Bickerdike Lsd 16-6-52-18-W5 53°28'N, 116°38'W	6-8' thick bentonite bed, sample from 2-3' below top of bed, at McLeod River water level, Paleocene
19	4981	Bryan Mountain NW9-49-21-W5 53°13'N, 117°00'W	Bentonite from top of lower coal seam in strip pit; Paleocene
20	4343	Little Red Deer Valley, NW34-28- 6-W4, 51°26'N 114°45'W	4" thick bentonite 3' below base of Paskapoo, Wildcat Hills map sheet (W 1/2); Upper Cretaceous
21	4982	Whitecourt, 54°05'N 115°31'W	Pembina coal seam; Uppermost Cretaceous

No.	Departmental No.	Location	Description and Stratigraphic Location
22	4983	Hell Creek State Park, Montana S1/2-35-21-37E 47°36'N, 106°55'W	2-3" bentonite below 20" coal, above 3' lignite, Z-Coal at Hell Creek-Fort Union contact; Cretaceous-Tertiary boundary coal, Hell Creek
23	3056] 3058]	Strawberry Creek Lsd 4-5-50-2-W5 53°17'N, 116°06'W	Bentonite from Kneehills Tuff Zone, Upper Cretaceous

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